

Ray tracing of ion-cyclotron waves in a coronal funnel

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Abstract. Remote observations of coronal holes have strongly implicated the kinetic interactions of ion-cyclotron waves with ions as a principal mechanism for plasma heating and acceleration of the fast solar wind. In order to study these waves, a linear perturbation analysis is used in the work frame of the collisionless multi-fluid model. We consider a non-uniform background plasma describing a funnel region and use the ray tracing equations to compute the ray path of the waves as well as the spatial variation of their properties.

1 Introduction

The ultraviolet spectroscopic observations made by SUMER and UVCS aboard SOHO indicated that heavy ions in the coronal holes are very hot with high temperature anisotropy (see, e.g., Kohl et al. 1997; Wilhelm et al. 1998). This result is a strong indication for heating by ion-cyclotron resonance (i.e., collisionless energy exchange between ions and wave fluctuations, see Stix 1992, Chap 10) involving ion-cyclotron waves that are presumably generated in the lower corona from small-scale reconnection events (Axford & McKenzie 1995). Performing a Fourier plane wave analysis, ion-cyclotron waves are studied using the collisionless multi-fluid model. While neglecting the electron inertia, this model permits the consideration of ion-cyclotron wave effects that are absent from the one-fluid MHD model. Realistic models of density and temperature as well as a 2D funnel model describing the open magnetic field are used to define the background plasma. Considering the WKB approximation, we first solve locally the dispersion relation and then perform a non-local wave analysis using the ray-tracing theory, which allows to compute the ray path of the waves in the funnel as well as the spatial variation of their properties.

2 Basic equations

The cold collisionless fluid equations for a particle species j are:

$$\frac{\partial n_j}{\partial t} + \nabla \cdot (n_j \mathbf{v}_j) = 0, \quad (1)$$

$$m_j n_j \left(\frac{\partial \mathbf{v}_j}{\partial t} + \mathbf{v}_j \cdot \nabla \mathbf{v}_j \right) - q_j n_j (\mathbf{E} + \mathbf{v}_j \times \mathbf{B}) = 0, \quad (2)$$

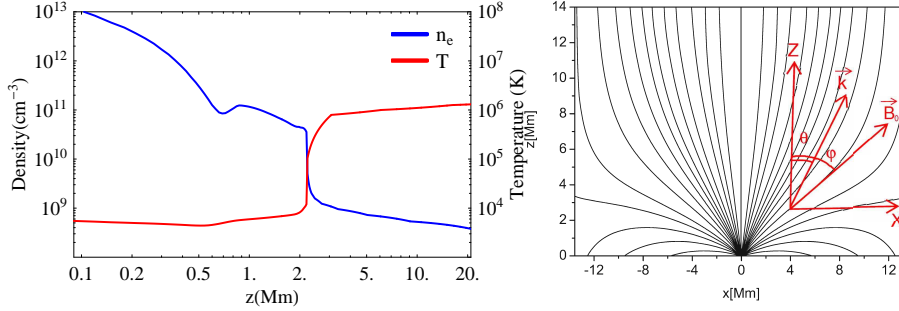


Figure 1. Left: Electronic density (n_e) and temperature (T) model-profiles of the chromosphere (Fontenla et al. 1993) and the lower corona (Gabriel 1976). Right: Funnel magnetic field geometry as obtained from a 2-D potential field model (Hackenberg et al. 2000).

where m_j , n_j and \mathbf{v}_j are respectively the mass, density and velocity of a species j . The electric field \mathbf{E} and the magnetic field \mathbf{B} are given by Faraday's law, i.e. $\nabla \times \mathbf{E} = -\partial \mathbf{B} / \partial t$. The background density, temperature and magnetic field are described in Fig. 1. Considering the quasi-neutrality and no ambient electric field, we perform a Fourier plane-wave analysis. The dispersion relation is obtained using

$$D(\omega, \mathbf{k}, \mathbf{r}) = \text{Det} \left[\frac{c^2}{\omega^2} \mathbf{k} \times (\mathbf{k} \times \mathbf{E}) + \boldsymbol{\varepsilon}(\omega, \mathbf{k}, \mathbf{r}) \cdot \mathbf{E} \right] = 0, \quad (3)$$

where c is the speed of light in vacuum, $\boldsymbol{\varepsilon}$ is the dielectric tensor which is a function of the wave frequency ω , the wave vector \mathbf{k} and the large-scale position vector \mathbf{r} . The wave vector \mathbf{k} lies in the $x - z$ plane, with $\mathbf{k} = k(\sin\theta, 0, \cos\theta)$.

The dispersion relation (3) is used to compute the Hamiltonian-type ray-tracing equations (Weinberg 1962):

$$\frac{d\mathbf{r}}{dt} = -\frac{\partial D(\omega, \mathbf{k}, \mathbf{r}) / \partial \mathbf{k}}{\partial D(\omega, \mathbf{k}, \mathbf{r}) / \partial \omega}, \quad \frac{d\mathbf{k}}{dt} = \frac{\partial D(\omega, \mathbf{k}, \mathbf{r}) / \partial \mathbf{r}}{\partial D(\omega, \mathbf{k}, \mathbf{r}) / \partial \omega}. \quad (4)$$

3 Numerical results

We consider a cold plasma made of electrons (n_e), protons (n_p) and alpha particles (He^{2+} , indicated by α) with $n_\alpha = 0.1n_p$. In this case, the dispersion relation (3) is a quadratic polynomial of degree 6, which means that 3 modes exist and each one is represented by an oppositely propagating ($\omega > 0$ and $\omega < 0$) pair of waves. These modes, for which the dispersion curves are shown in the right panel of Fig. 2, are the ion-cyclotron modes 1 (IC1) and 2 (IC2) and the fast mode. For large k , the two IC modes reach a resonance regime at each one of the ion-cyclotron frequencies, i.e. $\omega = \Omega_p$ and $\omega = \Omega_\alpha = \Omega_p/2$. The fast mode has a cut-off frequency $\omega_{co}/\Omega_p = 0.583$ and couples and mode converts with the IC1 mode at the so-called cross-over frequency $\omega_{cr}/\Omega_p = 0.612$. The polar plots of the group velocity for $kV_{Ap}/\Omega_p = 0.2$ (Fig. 2), show that the IC2 mode is mainly anisotropic and cannot propagate perpendicularly to \mathbf{B}_0 . Thus the corresponding energy mainly flows along the magnetic field lines, with maximum group velocity at parallel propagation. On the other hand, the IC1

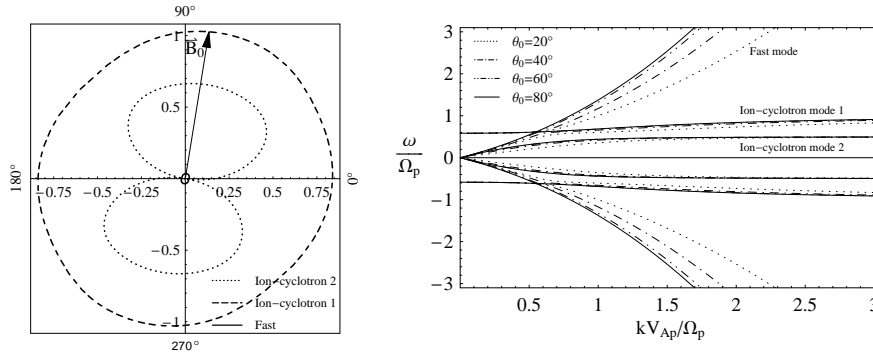


Figure 2. Right: Dispersion curves in the cold three-fluid (e-p-He²⁺) model at the location ($x=7.5$ Mm, $z=2.5$ Mm) in the funnel with a \mathbf{B}_0 -inclination angle $\varphi \approx 79^\circ$ and for different propagation angles θ (Ω_p and V_{Ap} are the proton cyclotron frequency and Alfvén speed). Left: Polar plot of the group velocity as a function of θ and for $kV_{Ap}/\Omega_p = 0.2$.

mode and the fast mode propagate almost isotropically, and consequently the energy flow is fairly isotropic. These results are confirmed by the ray-tracing computation which clearly shows that the IC2 mode is well guided along the field lines, since the ray paths (direction of the group velocity) for various initial angles of propagation θ_0 nicely follow the magnetic field lines (Fig. 3). Indeed, the maximal angular deviation is $\psi \approx 6.5^\circ$ at $z \approx 4$ Mm and $\psi \approx 0^\circ$ (quasi-parallel propagation) in the upper part of the funnel, where the wave is quasi-electrostatic, i.e. $|\xi| \approx 1$, and has a nearly linear polarization, i.e. $|\varrho| \approx 0$. On the contrary to that behavior, the IC1 mode and the fast mode are unguided with a ray path having mainly a strait trajectory. The angular deviation ψ between the ray path and \mathbf{B}_0 varies between -60° and 80° for the IC1 mode and -40° and 60° for the fast mode. The polarization is in general elliptical, right-handed ($\varrho > 0$) for the IC1 mode and left-handed ($\varrho < 0$) for the fast mode, except for $\theta = 20^\circ$ in the upper part of the funnel ($z \gtrsim 6$ Mm) where it is mainly circular, right-handed ($\varrho = -1$) for the IC1 mode and left-handed ($\varrho = -1$) for the fast mode.

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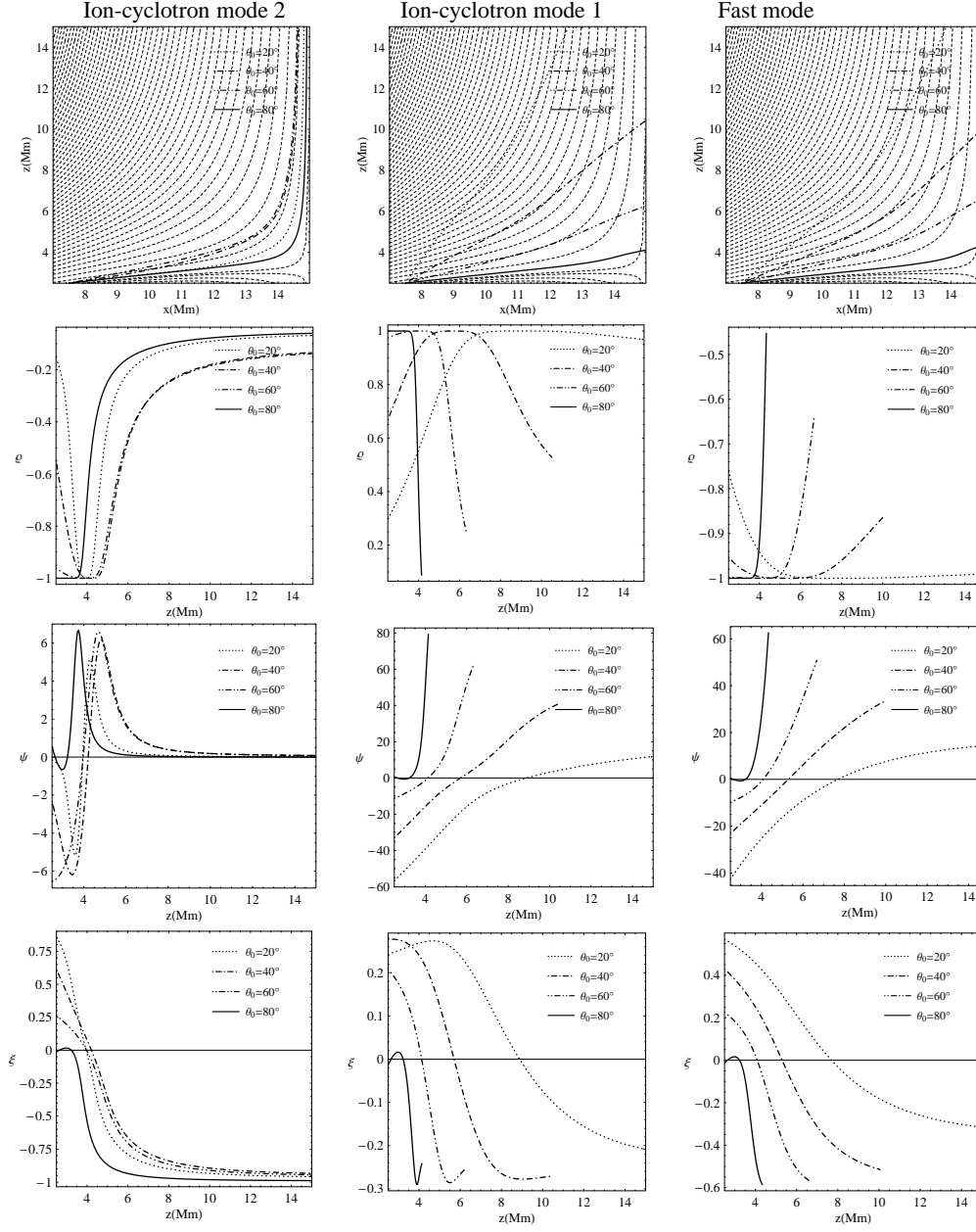


Figure 3. Ray paths of the waves and the spatial variation of their basic properties. The waves are launched at the location ($x_0=7.5$ Mm, $z_0=2.5$ Mm) in the coronal funnel (with a \mathbf{B}_0 -inclination angle $\varphi_0 \approx 79^\circ$) with an initial normalized wave number $k_0=0.2$ and different initial angles of propagation θ_0 . In the top panels, the dashed lines represent the funnel field lines. The wave properties are: (Q) helicity (degree of circular polarization), (ψ) angle between the direction of the group velocity and \mathbf{B}_0 , (ξ) the electrostatic part of the wave.